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Control strategy for a Solid Oxide Fuel Cell fueled by Natural Gas operating in Distributed Generation

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Abstract

The paper presents a control strategy concept for a Solid Oxide Fuel Cell (SOFC) to work in Distributed Generation. The control strategy is based on several factors and directs the operation of the SOFC in the context of changes occurring in the market, while taking into account the operating characteristics of the power unit. The control strategy is defined by an appropriate objective function: for example, work at maximum profit, maximum service life, etc. The results of simulations of a fuel cell at chosen loads are presented. Daily changes in the prices of fuel and electricity are factored into the simulations.

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1. Introduction

The Distributed Generation (DG) system has many advantages, including very high certainty of supply, high efficiency power generation (electricity as well as heat and power generation) and high adaptability to changes in demand (both daily and annual). The DG system can be compared in its essence and mode of operation to the Internet or to mobile networks.

Sources in a distributed system can operate in one of many variants, depending on the individual preferences of the operator. One option is to work for maximum profit—increasing the supply of high-margin power sources, another is to boost the longevity of equipment in order to avoid additional starts

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and stops, and yet another might be to provide maximum subsistence for a customer's needs (e.g. hospitals). Most operators will probably devise a blend of factors depending on their individual circumstances. An interconnected network of small sources, and their cooperation with the electricity network might add one extra layer of complexity: the operator may cede control of the source to a larger operator who, through control of a large number of similar sources, may have a power comparable to that of a classic large power plant. A network of sources and combined operational control would change power relations.

An electricity distribution system based on a network of small, interconnected sources is characterized by both load variability and changing electricity prices. This means that the sources will have to adapt to the load not only for local changes, but also as it relates to the market balance between buyers and sellers of power to the grid and changes in fuels markets.

Current trends in energy and fuels on the market lends additional influence to all those issues. There are here the following options: operation of the device at a cost below the purchase price (Bid), operation at a cost between the sale price (Ask) and the Bid price; operation at a cost above the Ask price. Additionally, some operators may cooperate with the distribution network to provide system solutions and situations may arise when the source is disconnected from the network ('island operation').

The selection of individual sources working in a distributed system is a complex issue [1]. Until now, research work on source operation in DG has focused on issues of electrical [2] synchronization with the network, the impact of noise generated, etc. Issues relating to long-term source operation are virtually unrecognized and unexplored. The analysis available applies only to selected elements of the work of DG sources.

In [3] sources that can operate as a distributed source were classified: (i) Reciprocating engines; (ii) Gas turbines [4]; (iii) Stirling engines [5]; (iv) Combination systems based on gas turbines [6] and reciprocating engines; (v) Small hydro, wind power; (vi) Photovoltaic systems [7]; geothermal power plants [8]; (vii) Fuel cells [9, 10]; and (viii) Systems using: biomass [11–13] and waste, tides, currents, waves and warm seas.

Most available studies almost exclusively concern the issues of electrical and electronic collaboration between the DG source and the power system [3]. The time periods considered there are below 1 second. The proposed variants are closely related to the network source (e.g. through an intermediate network of DC). Issues are also dealt with the same power grid work [14] including the determinants of transmission. The behavior of the power grid of connected sources distributed in emergency situations [15] also on electrical issues was also analyzed.

Control of multiple DG sources via the Internet was subject to study [16], which also took into account the economic aspects of making sources work together. A simulator running in real mode was created [17] to analyze power source co-operation with the network, but it only studied electric co-operation with the network source. An analyzed time frame of less than 100 micro seconds was concerned. Analysis of the work of the same sources from the standpoint of efficiency and power were also carried out, as well as opportunities to work in co-generation [18]. There were attempts to use artificial intelligence to predict the safe operation of sources involved in the distributed system [19].

Economic issues of implementing a DG system were analyzed, among others in [20]. Attention was paid to the environmental aspects of the application of DG sources on a larger scale. Technical and economic analysis and a comparison of a piston engine with a μ -gas turbine is presented in [21], which implies that the piston engine achieves a positive NPV after 5 years (for μ -turbine, this time is almost 8 years).

Decentralized systems are beginning to prevail over centralized models. Very eloquent examples, schematically, are provided by mobile phone networks and the Internet. It is expected that Distribution Generation [22] consisting of many small units will dominate in the near future. In this system, electricity

will be produced by small sources installed directly alongside consumers of energy and working mainly to meet their needs. These sources must meet specific requirements including: high generating efficiency, providing most of the energy needs of a facility and possibly providing a small amount of delivered fluids (such as fuel only).

As we can see from literature data, the problem with load or demand for electricity forecasting has been pretty well researched, but the ways of using such information for devices working in a distributed generation system have not been analyzed.

2. Theory

2.1. Solid Oxide Fuel Cell

It is very difficult to find the characteristics of such devices when the load changes. However, managed to find appropriate characteristics for a relatively large object (250 kW), it was assumed that smaller devices will behave similarly in this way managed to build suitable for further analysis of the characteristics of the device – Fig 1.

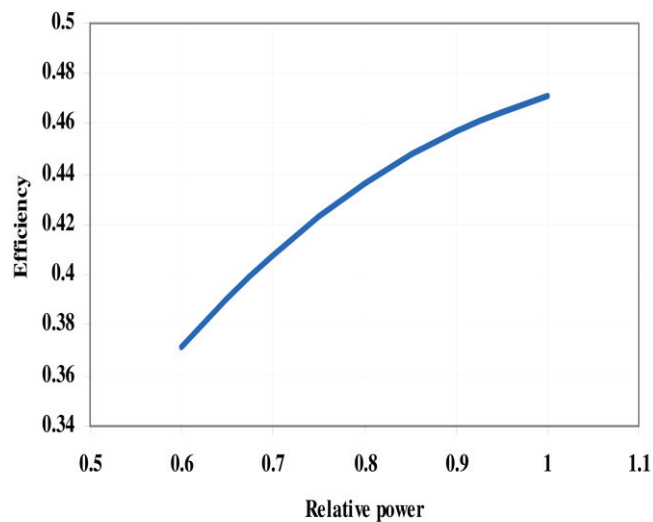


Fig. 1. Efficiency of SOFC (based on [23])

In [23] the lowest relative load was 0.56 but for this calculations that value was assumed as 0.6.

Changes in the efficiency of the Solid Oxide Fuel Cell during load changes can be approximated by the following relationship:

$$\eta = \left(0.8421 - 0.3711 \frac{P}{P_0} \right) \cdot \frac{P}{P_0} \quad (1)$$

where: η – SOFC efficiency, P – power, P_0 – nominal power.

To have reasonable profits the power of the fuel cell was chosen so that the minimum demand was equal to 60% of the SOFC load.

2.2. Costs

In order to reduce electricity costs the possibility of using a single-zone tariff of electricity in cooperation with a natural gas-powered Solid Oxide Fuel Cell was studied.

Fixed costs include license fees for electricity, which for the tariffs used in this analysis are about \$3.49/month gross (tariff G11 relating to power companies: “ENERGA-OBRÓT S.A.” and “Energia Operator S.A”). They also include a fixed charge of \$37.71/month gross for gas (transmission & distribution charged by the company “PGNiG”).

Table 1. Variable costs of electricity by tariff G11 relating to power companies: “ENERGA-OBRÓT S.A.” and “Energia Operator S.A”

Variable cost	\$/kWh
electricity	0.11
transmission	0.08

Variable costs include primarily the purchase of electricity (Table 1) and the scales of the gas group of “PGNiG” in tariff w-5 for fuel only (\$0.415/Nm³) and tariff E-1A for transmission (\$0.011/Nm³).

Revenues include above all the avoided costs of purchasing electricity when producing it is a cheaper way of meeting demand.

3. Optimal control strategy of a Solid Oxide Fuel Cell unit for DG operation

The information about the demand was collected for part of the Institute of Heat Engineering and Central Canteens of Warsaw University of Technology. The scope of data taken into account for this consideration was one week – from 17.10.2011 to 23.10.2011.

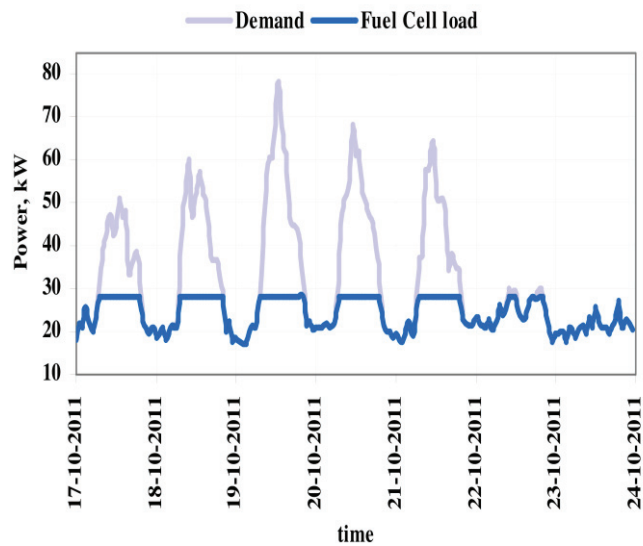


Fig. 2. Demand vs optimal load of SOFC

The optimal way of meeting demand of part of the complex of buildings using Solid Oxide Fuel Cell and power from grid was shown in Figure 2. As we can see from that graph fuel cell work continuously all considered week and its size was chosen that 60% of its load is equal to minimum demand. But if it happened that the demand would be lower the excess electricity from SOFC must be sold to avoid switching on and off the device.

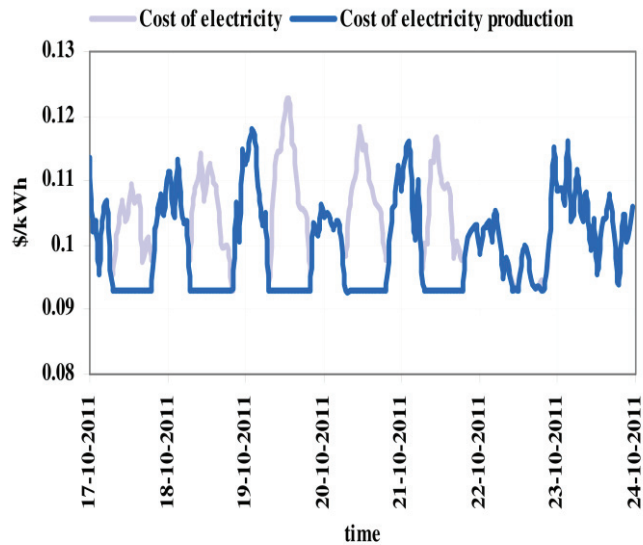


Fig. 3. Cost of electricity vs cost of electricity production

Figure 3 shows the cost of producing electricity and its cost at the optimal operating strategy. The first one ranged from \$0.09 to almost \$0.12, depending on fuel cell efficiency. The second one reached value from \$0.09 (only fuel cell at maximum load – maximum efficiency) to little more than \$0.12 (SOFC at maximum load and power from grid).

Thanks to this combination, the average cost of electricity was always less than electricity from grid – see Table 1.

For the considered week the difference in variable costs was \$555/week. After taking into account the fixed costs, the income associated with the proposed solution was \$546/week.

4. Conclusions

The control strategy for the SOFC stand-alone unit as a DG source of power is presented. From the investigations performed, it was determined that the most appropriate objective function of the strategy is to operate the SOFC for maximum life (defined as maintaining high cell temperature). To have quite good profits for this situation fuel cell can not be oversized, which means that in cases of high demand for power from the customer, the electricity should be bought from the network. On average, the SOFC is never turned off, even in cases of low electricity demand, or low electricity prices in the network.

Profits from operation of the SOFC depend strictly on the load profile and for the case at hand it was \$546/week.

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